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Review

Lagrangian ocean analysis: Fundamentals and practices

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ABSTRACT

Lagrangian analysis is a powerful way to analyse the output of ocean circulation models and other ocean velocity data such as from altimetry. In the Lagrangian approach, large sets of virtual particles are integrated within the three-dimensional, time-evolving velocity fields. Over several decades, a variety of tools and methods for this purpose have emerged. Here, we review the state of the art in the field of Lagrangian analysis of ocean velocity data, starting from a fundamental kinematic framework and with a focus on large-scale open ocean applications. Beyond the use of explicit velocity fields, we consider the influence of unresolved physics and dynamics on particle trajectories. We comprehensively list and discuss the tools currently available for tracking virtual particles. We then showcase some of the innovative applications of trajectory data, and conclude with some open questions and an outlook. The overall goal of this review paper is to reconcile some of the different techniques

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and methods in Lagrangian ocean analysis, while recognising the rich diversity of codes that have and continue to emerge, and the challenges of the coming age of petascale computing.

1. Introduction

The ocean exhibits a huge range of dynamical motions, spanning scales from millimetres to thousands of kilometres. As seawater moves, each fluid particle carries tracers such as salt, nutrients, heat, as well as particulate matter such as plankton and marine debris. For various theoretical and practical applications, we are interested in how water moves between ocean regions. That is, we are interested in mapping out pathways of seawater motion, since the transport of seawater and its tracer content, as well as the pathways and timescales for that transport, are key facets in how the ocean plays a role in climate and marine ecology.

1.1. Estimating pathways

There are two general methods for estimating pathways in the ocean. One method makes use of tracers, such as the multitude of age tracers described by Mouchet et al. (2016) and references therein. Tracer studies are well suited for Eulerian methods, which make direct use of ocean velocity fields on their native grids.

The second approach makes exclusive use of the Lagrangian perspective of fluid dynamics (e.g., Bennett, 2006). This method employs an ensemble of virtual (passive) Lagrangian particles of zero spatial extent whose trajectories are determined by the velocity field.[1] The velocity fields that are used to move the particles often come from OGCMs, although there are interesting application using observational-based velocities such as surface geostrophic velocities based on satellite altimetry (e.g. d'Ovidio et al., 2009; Klocker and Abernathey, 2014), or measured by high frequency (HF) radar (e.g. Ullman et al., 2006).

Trajectories for virtual particles map out pathlines of the velocity field, often including the effect of subgrid scale diffusion. Statistics of the trajectories then define particle pathways and their associated time scales. By following the flow of virtual particles, and possibly assigning non-zero transports and other properties to them in post-processing, questions about pathways and flow connectivity can be addressed.

This review focuses on Lagrangian analysis methods facilitated by virtual particles in the open ocean. We are partly motivated by the growing array of floating instruments in the ocean along with the improving Lagrangian simulation capabilities. There is a corresponding need to review the methods and foster new ideas for extracting information about the ocean circulation from the entangled trajectories of floats and/or simulated particles. We thus aim to summarize the state of the science in Lagrangian modelling and analysis, focussing on the large scale open ocean circulation, hoping to support a new generation of scientists contributing to the development and use of the methods.

Our presentation is aimed at graduate students, though any large-scale oceanographer or mathematician with an interest in virtual particle analysis could use this paper as a starting point. In that sense, this paper is intended as an accompanying paper to Griffies et al. (2000), which provided an introduction to primitive equation ocean models and to Ådlandsvik et al. (2009), which gave an overview of Lagrangian modelling practice from a marine biology perspective.

1.2. Overview of Lagrangian ocean analysis

Observationalists have been tracking the ocean in a Lagrangian fashion since the very early ages of oceanography. Movements of the currents were documented using either ship drift or the drift of purposely built (subsurface) floats (e.g., Swift and Riser, 1994). Many observations remain inherently Lagrangian, such as the trajectories of surface drifters shown in Fig. 1 (Lumpkin and Pazos, 2007), the subsurface Argo floats (Lebedev et al., 2007; Ollitrault and Rannou, 2013), and the tracking of fish larvae (Paris et al., 2013a) and turtle hatchlings (Scott et al., 2014).

Lagrangian analysis through virtual particle tracking within OGCMs began in the 1980s, on small-scale structures, with studies on a theoretical box-model (Awaji et al., 1980) as well as a model that incorporated hydrographic data and realistic topography (Imasato et al., 1980). The Lagrangian framework of these small-scale examples was then applied to the velocity-field output of basin-scale, three-dimensional numerical experiments. Examples include regional deep ocean circulation (Fujio and Imasato, 1991), western boundary currents (Imasato and Qiu, 1987), fronts (Pavia and Cushman-Roisin, 1988) and gyre transport (Böning and Cox, 1988). Particle trajectories in global ocean circulation models, driven by global hydrographic and wind observations, were first achieved in the 1990s (Fujio et al., 1992; Döös, 1995; Drijfhout et al., 1996; Blanke and Raynaud, 1997).

In recent years, more than 100 articles per year are published with the words 'Lagrangian Ocean Modelling' as the topic, according to the Web of Science. These papers include studies on the pathways of virtual particles that simulate sea water pathways, as well as explicit tracking of tracers such as nutrients (e.g. Chenillat et al., 2015; Jönsson et al., 2011) and particulates such as larvae (e.g. Cowen et al., 2006; Paris et al., 2005; Teske et al., 2015; Cetina-Heredia et al., 2015; Phelps et al., 2015), plastics (e.g. Lebreton et al., 2012), microbes (e.g. Hellweger et al., 2014), planktic foraminifera (e.g. van Sebille et al., 2015), jellyfish (e.g. Dawson et al., 2005), icebergs (e.g. Marsh et al., 2015), surface drifters (e.g. Kjellsson and Döös, 2012b), oil droplets (e.g. Paris et al., 2012), eel (e.g. Baltazar-Soares et al., 2014), pumice (e.g. Jutzeler et al., 2014) and many more.

The ocean circulation covers an enormous range of scales and regions. As said above, in this review we focus primarily on applications on the basin and global scales. However, it should be noted that there is also extensive Lagrangian analysis work done on smaller scales, such as in coastal zones and recently in the Gulf of Mexico through interest in dispersion of the DeepWater Horizon oil spill (e.g. Beron-Vera and LaCasce, 2016; Haza et al., 2016).

The Lagrangian framework is not only used to analyse velocity fields by computing their integral curves, but also to directly solve for the trajectory by casting the equations of motion in a Lagrangian framework (Bennett, 2006). Lagrangian methods are widely used in engineering, including Discrete Element Methods (e.g. Kruggel-Emden et al., 2008) and Smoothed Particle Hydrodynamics (e.g. Cummins et al., 2012). While advances in this field have been made in large scale oceanography, both for sub-components of ocean models (e.g. Bates et al., 2012) and for fully Lagrangian ocean models (Haertel and Randall, 2002; Haertel and Fedorov, 2012), this topic is not the focus of this review. Instead, we focus on Lagrangian diagnostic methods to identify oceanic pathways.

The Lagrangian framework for analysing pathways is complementary to the analysis of tracers. One of the key differences is the computational cost. For each time step, movement of a Lagrangian particle takes only one set of computations. In contrast, the advection-diffusion of a tracer concentration takes N sets of computation, where N is the number of discrete ocean grid cells. While one Lagrangian particle trajectory does not allow for meaningful analysis of ocean pathways, this comparison does show that the computational scaling of the two

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[1] Lagrangian particles are also sometimes called 'e-floats' by, for example, Bower et al. (2009).